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NRL Memorandum Report 3894

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An Investigation into the Causes of Ceramic Cracking in the Mark 11 Source (400 Series)

10 R.C. POHANKA, P.L. SMITH and P.C. MILLER

Ceramics Branch
Material Science and Technology Division

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Washington, D.C.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 3894	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) AN INVESTIGATION INTO THE CAUSES OF CERAMIC CRACKING IN THE MARK 11 SOURCE (400 SERIES)		5. TYPE OF REPORT & PERIOD COVERED Summary Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. C. Pohanka, P. L. Smith and P. C. Miller		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D. C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Problem PO3-03A
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command Code 660T Washington, D.C. 20362		12. REPORT DATE December 7, 1978
		13. NUMBER OF PAGES 29
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fracture	Ceramic
Flaw size	Proof testing
Stress	Quality assured
Strength	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In summary, this investigation has shown that 10% of the Edo-Western ceramics used in the Bendix source are weak, that is, they fail at hoop tensile stresses of 5000 psi or less, and a few fail at stresses as low as 1000 psi. It was found that a proof test of the elements of 6000 psi would eliminate the weak ceramics without damaging the survivors.

All in-service failures (from environmental testing or handling) were found to occur in ceramic elements which contained large flaws or other defects. The strength of these was calculated to be

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20. Abstract (Continued)

6000 psi or less, and the strength distribution was significantly different from normal Edo-Western ceramics. The fracture of the in-service failed elements was due to hoop tension which arises from the action of the neoprene spacer under axial compression. All service failures occurred either at solder joints or from edge defects at the non-bonded side of the element.

Strength degradation was found in Edo-Western ceramics that had seen either shipping and handling or environmental testing. This degradation could be significant if re-use of the source is planned.

Strength tests of General Electric ceramics (including a 6000 psi proof test) showed that all the General Electric elements were stronger that 6000 psi and on the average 1500 psi stronger than Edo-Western.

It was shown that the hoop stresses which cause failure of the ceramic arise from the motion of the neoprene spacer under axial compression. Tests made by axial loading of a full stack and a number of mini-stacks containing one to four rings showed that the shortest ring (#2) is the most vulnerable to fracture under axial loading. Experimental work at NRL supplemented by theoretical analysis at NSWC showed that two mechanisms were responsible for the development of hoop stress in the ceramic under axial load. The first is the lateral expansion of the neoprene, thereby filling the gap between the spacers and then exerting outward pressure on the ceramic resulting in hoop tension. The second source of hoop tension is the friction between the ceramic and the neoprene. Under axial compression, the neoprene flows over the surface of the ceramic and friction sets up a hoop tension in the ceramic. Modification of the spacer to provide more space for the neoprene to flow resulted in an increase of 1.5 times in the axial force necessary to cause fracture of the ceramic in the most vulnerable regions (the three smallest rings). Further modification of the spacer combined with an improved surface finish of the ceramics increased the axial failure load for Ring #2 by 5 times. These changes raise the most vulnerable region to values equal to those of the larger rings.

All stack tests were made on unbonded ceramics. The effects of bonding on the resistance of the stack to fracture under axial compression are not known and may be significant. Tests will be made as soon as bonded mini-stacks are made available by Bendix.

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AN INVESTIGATION INTO THE CAUSES OF CERAMIC CRACKING IN THE MARK 11 SOURCE (400 Series)

SUMMARY OF TASK 1 RESULTS

The service failures were shown to be due to hoop stresses in the ceramic. All service failures (from environmental testing or handling) occurred in elements which contained large flaws. The strength of these elements was calculated to be 6000 psi or less and the strength distribution was significantly different from normal Edo-Western ceramics. All service failures originated either at solder joints or at large flaws on the non-bonded side of the ceramic.

Strength tests of a large group of Edo-Western ceramics showed that ~ 10% of the ceramics used fail at 5000 psi or less and a few failed at stresses as low as 1000 psi. It was shown that a proof test at 6000 psi would eliminate the weak ceramics without damaging the survivors.

Strength degradation was found in Edo-Western ceramics that had seen either shipping and handling or environmental testing. This degradation could be important if re-use of the source is planned.

Tests of General Electric ceramic (including a 6000 psi proof test) showed all General Electric ceramics to be stronger than 6000 psi and on the average the General Electric ceramics were 2500 psi stronger than Edo-Western.

SUMMARY OF TASK 2 RESULTS

It was shown that the hoop stresses which cause failure of the ceramic arise from the motion of the neoprene spacer under axial compression. Tests made by axial loading of a full stack and a number of mini-stacks containing one to four rings showed that the shortest ring (#2) is the most

Note: Manuscript submitted October 12, 1978.

vulnerable to fracture under axial loading. Experimental work at NRL supplemented by theoretical analysis at NSWC showed that two mechanisms were responsible for the development of hoop stress in the ceramic under axial load. The first is the lateral expansion of the neoprene, thereby filling the gap between the spacers and then exerting outward pressure on the ceramic resulting in hoop tension. The second source of hoop tension is the friction between the ceramic and the neoprene. Under axial compression, the neoprene flows over the surface of the ceramic and friction sets up a hoop tension in the ceramic. Modification of the spacer to provide more space for the neoprene to flow resulted in an increase of 1.5 times in the axial force necessary to cause fracture of the ceramic in the most vulnerable regions (the three smallest rings). Further modification of the spacer combined with an improved surface finish of the ceramic increased the axial failure load for Ring #2 by five times. These changes raise the most vulnerable region to values equal to those of the larger rings.

All stack tests were made on unbonded ceramics. The effects of bonding on the resistance of the stack to fracture under axial compression are not known and may be significant. Tests will be made as soon as bonded mini-stacks are made available by Bendix.

BACKGROUND

Eleven sources of the 400 series of the Mark 11 transducer failed in shipping or testing. Seven of these eleven had cracked ceramic which provided a total of nineteen cracked elements (rings). Eleven of these nineteen elements were recovered and sent to NRL for analysis of the fractures. Examination of the cracked elements showed that all had failed from hoop tension in the ceramic. Examination of the structure of the transducer suggested that the source of hoop tension was associated with the neoprene spacers.

At the request of PMS-407, R. Heaney, NAVSEA 660T set up a design review team to assist in improving this transducer. NRL suggested the following two tasks for its contribution to this review.

The first task was an analysis of the fractured ceramics which occurred in shipping or testing. This analysis included an assessment of the quality of the ceramic as well as remedial action that insures the quality of future ceramics.

The second task was to investigate the source of the

hoop tensile stresses responsible for cracking and to suggest possible design changes which would reduce these stresses. The experimental work carried out at NRL was supplemented by a theoretical study using finite element analysis by Pao Huang of NSWC.

TASK 1. FRACTURE ANALYSIS AND EVALUATION OF THE CERAMIC QUALITY IN THE MARK 11 400 SERIES SOURCE

INTRODUCTION

The fracture surfaces of the "service" failed ceramics as well as those fractured in the laboratory were examined by optical and Scanning Electron Microscopy (SEM). This examination permits the origin of the fracture to be located and the size of the flaw responsible for the fracture to be measured. The stress in the ceramic at failure can then be estimated from the flaw size and fracture mechanics theory. The estimate of the failure stress is based on the assumption that the ceramic is normal. Thus, this estimate provides an upper limit to the stress and if the ceramic microstructure is unusual the estimate of failure stress could be high.

The microscopic examination also provides an assessment of the quality of the ceramic. Grain and pore size and distribution can be measured and compared to earlier data on ceramic of the same type and manufacturer.

Strength measurements of unfailed ceramic elements were also made and the fracture surfaces examined for comparison with the fractures occurring in "service." Fractures of the ceramics which failed in shipping and testing are referred to as "service fractures" to distinguish them from the fractures obtained in laboratory tests. Flexure strength measurements on ring segments from both service and laboratory fractured rings were also carried out to further test and compare the strength distributions of the ceramics.

EXPERIMENTAL PROCEDURES AND RESULTS

A. Characterization and Failure Stress of In-Service Fractures.

The failed Edo-Western ceramics received from Bendix Corporation were characterized using optical and Scanning Electron Microscopy (SEM). The fracture origins were determined by tracing the "river" patterns to their initiation point (Figure 1). The flaws from which fracture initiated were measured. Two examples of fracture origins are illustrated in Figure 1. The specimen shown in Figure 1a failed from a flaw caused by soldering and Figure 1b from a surface

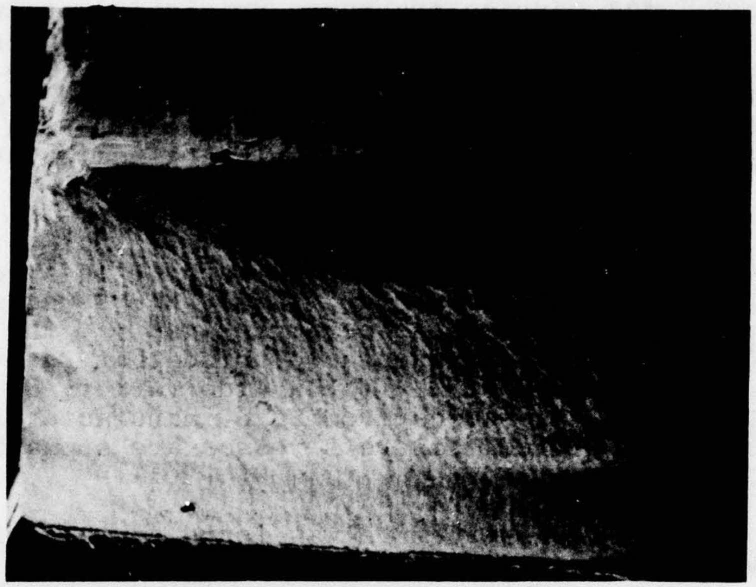

Fig. 1a — Failure from solder flaw x 20

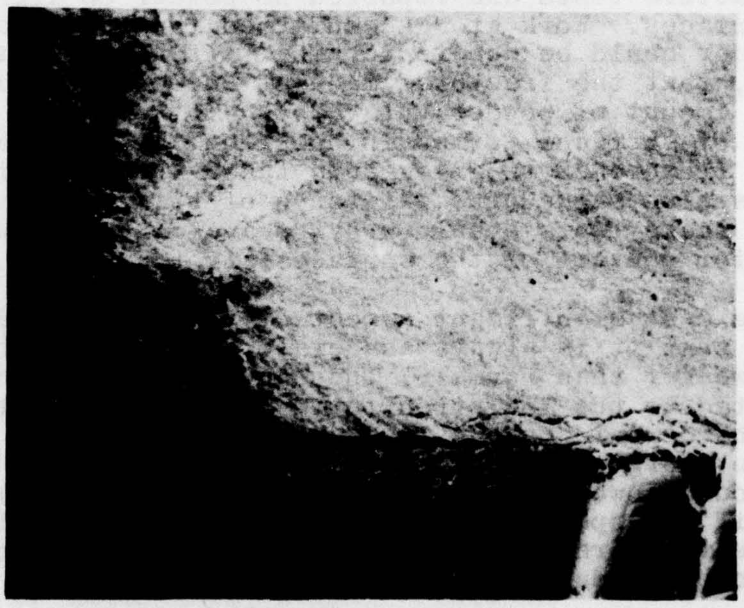

Fig. 1b — Failure from surface flaw x 50

flaw on the non-bonded side of the ceramic.

The results of the fracture analysis are summarized in Table 1. All service fractures originated at two places: a) at the inner diameter of the ceramic on the unglued side, and b) at or near a solder joint. The flaw size from which the fractures initiated was measured from the SEM photographs or by an optical microscope. From these measured flaw sizes, the stress at failure is calculated from:

$$\sigma = Y \sqrt{E\gamma/a} \tag{1}$$

where σ is the applied stress at failure, Y is a geometric factor (1.12 for semi-circular flaws), E = Young's modulus (8.13×10^{10} N/m^2) for these ceramics, and γ = the fracture energy (~ 4.0 J/m^2). It should be noted that Eq. (1) has been verified experimentally for a wide variety of lead zirconate titanate ceramics from U. S. manufacturers.[1,2] The calculated service failure stresses are summarized in Table 1.

An unusual microstructure was found at the origin of all service fractures and also at scattered points on the fracture surface. This structure consisted of pockets of sub-micron sized particles. Edo-Western suggested[3] that this powder was formed after fracture by rubbing of the fracture surfaces in subsequent handling. They carried out some fracture tests and reported no powder on freshly fracture surfaces. Work at NRL confirmed the fact that much of the powder could be due to rubbing. It was also found, however, that the fractures made at Edo-Western did contain a small amount of powder (Fig. 2b). In addition, SEM examination of surfaces formed in hoop tensile tests and in 3-point flexure on ring segments taken from in-service failures also showed the existence of this powder (Fig. 2a). Both of these tests should provide a clean break with little chance for contact of the surfaces after fracture.

The most significant aspect of the unusual microstructure is that it is always associated with specimens substantially weaker than normal. The unusual microstructure could be related to the low strength in two ways. First, if it is in the ceramic before fracture, it would lower both the fracture energy and the elastic modulus locally. Such effects would lower the calculated strength (Eq. (1)). Secondly, if the specimen powders during fracture, it would indicate the ceramic is friable and large flaws could be easily created during handling and assembly.

In any event, the only way to ensure ceramic of the appropriate quality (strength) is to proof test the ceramics

Table 1

SUMMARY OF SERIES 400 FAILURES AT NSWC						
Source SN	Test Phase Failed	Failure Description	NSWC Malfunction Report No.	Bendix Failure Analysis	NRL Ceramic Fracture Analysis: Primary Fracture Origin	NRL Ceramic Fracture Analysis: Failure Stress (psi)
4001	Periodic[1]	Failed Patterns after Leak Test	106480	Fractured Ceramic Y1,Y2,Y23,Y30,Y32	Non Bonded Corner	4950
		Failed Capacitance after Hydro. Pressure Test	106481	Leads loose Y1 silver pulled loose Y30 ceramic flake pulled loose	ID Surface Chip	5700-7000
				Leak at connector O Ring		
4005	Periodic	Failed IR and Capacitance after Hydro. Pressure Test	106482	Fractured Ceramic Y1, Y2, Y3, Y32		
				Leak at connector O Ring		
4020	Periodic	Failed IR and and Capacitance after T & H Test	106484	Fractured Ceramic Y32	Non Bonded Corner	5000
				Touch up silver paint across electrodes		
4002	Periodic Acceptance	Failed IR before Periodic Tests	106475	Cable leak	NA	NA
4019	Periodic	Failed Pattern and Capacitance after W/E sh	106486	Fractured Ceramic Y5, Y10, Y12, Y14, Y15, Y32	Solder Joint Y5, Y12, Y14, Y15	3600, 3000, 4900, 6260
					Bonded side Y10 Non Bonded side Y32	5700 5700
4011	Category[2]	Failed Patterns	106479	Fractured Ceramic Y14		
4029	Category	Failed Capacitance	106485	Poor lead connection at ceramic	NA	NA
4012	Category	Failed Patterns	106487	Fractured ceramic Y17		
4033	Category	Failed Patterns	106489	Fractured ceramic Y13		
4017	Category	Failed IR	106483	Contaminated Inductor Board	NA	NA
4013	Category	Failed IR	106488	Cable leak	NA	NA

NOTE

1. Periodic Quality Conformance Tests specified in WS 14052J, Paragraph 4.2.3
2. Category Testing Phase of the NSWC Certification Program for F.O.T. & E.

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Fig. 2a — Powder on NRL clean fracture surface x 5K
3 point flexure test

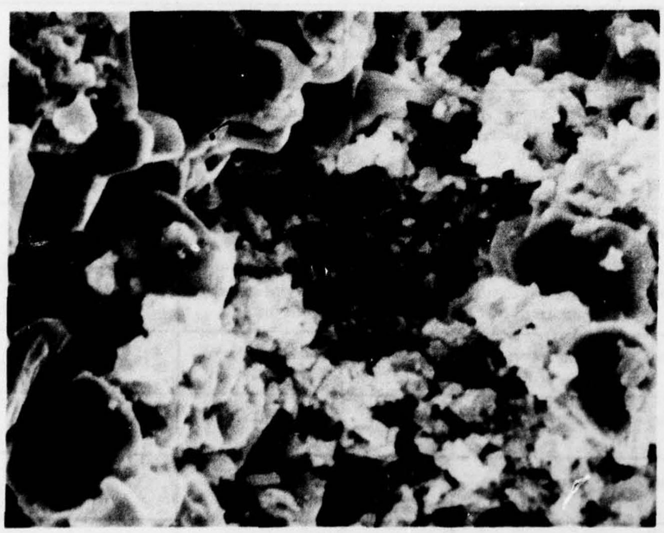

Fig. 2b — Powder on Edo-Western clean fracture surface
4 'Nutcracker' test x 5K

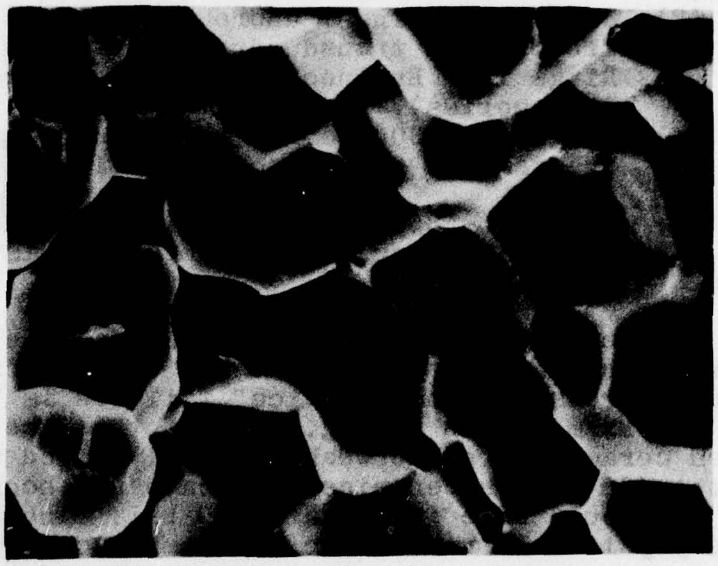

Fig. 2c — Normal microstructure in good quality Edo-Western ceramic — x5K

at the ceramic manufacturer. Any future strength problems would then be traceable to subsequent handling and assembly procedures.

B. Hoop Tension Strength Tests

The stress level required for the proof test can be determined from the analysis of failed specimens and strength tests on other samples. Hoop tensile strength tests were carried out on the appratus shown in Fig. 3. Strengths of the following five groups of specimens were measured.

(1) 400 series rings which had never been assembled.
(2) 400 series rings, unbroken ceramics recovered from failed transducers.
(3) Rings from Engineering Prototype Transducers (350 series).
(4) Rings from 300 series transducers.
(5) Unassembled rings from General Electric.

The rings from 350 and 300 series transducers had seen some service and testing but the detailed history is not known.

The percentage of failed ceramics at each level of stress is summarized in Figs. 4 and 5. The calculated failure stress for the "service" failures is included in Fig. 4. Examination of Fig. 4 shows that the "service" failed ceramics are the weakest - 90% failed at 6000 psi. For the 400 series ceramics that have not been assembled, only 10% would have failed at 6000 psi. Thus, a proof test at 6000 psi would remove the weak ceramic (approximately 10%).

To determine if the proof test causes any degradation in strength, a group of rings was first loaded to 6000 psi briefly, unloaded and then immediately reloaded to failure. Fig. 4 shows that this proof testing did not change the strength distribution from those whose strength was determined in a single stroke.

As also shown in Fig. 4 for this sampling (42 specimens), one very weak ring was found (less than 2000 psi). Thus, the proof test removes the weak specimens but does not degrade the strength of survivors.

For comparison purposes, General Electric ceramics were proof tested in similar fashion. Results are also shown in Fig. 4. All of the General Electric ceramics passed the proof test at 6000 psi and were, on the average, about 2500 psi stronger than the Edo-Western. These re-

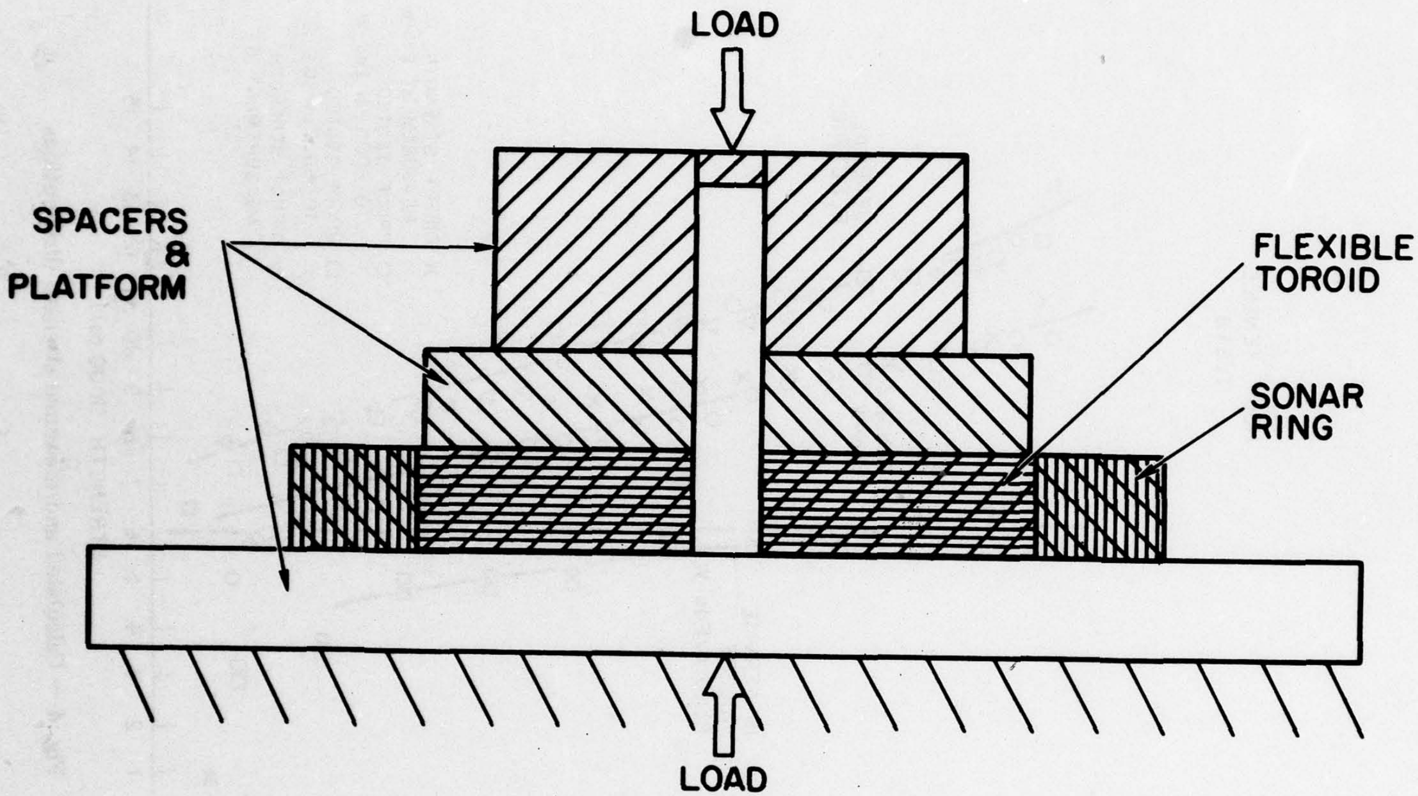

Fig. 3 — Schematic of hoop tensile test apparatus

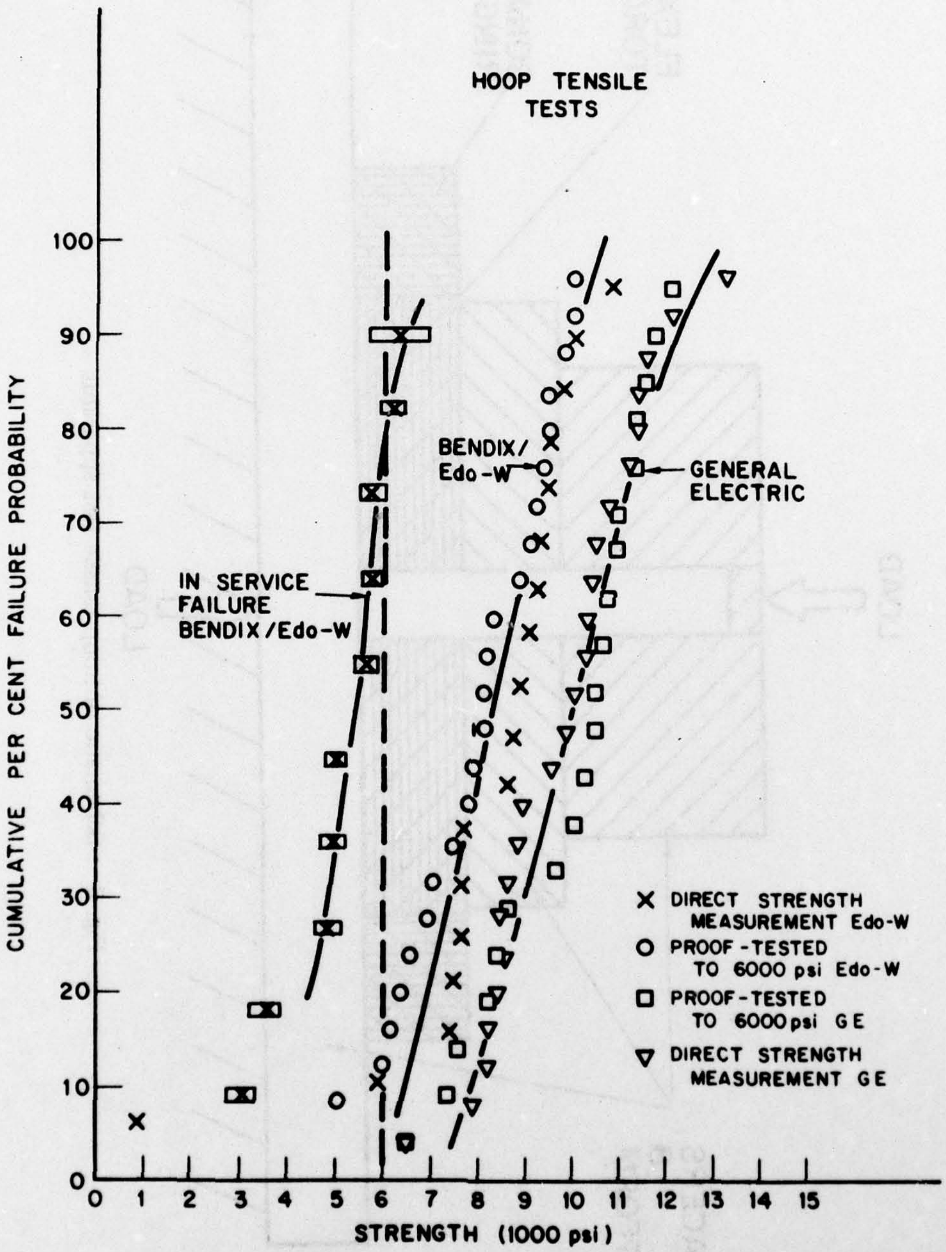

Fig. 4 — Calculated and measured strength distributions

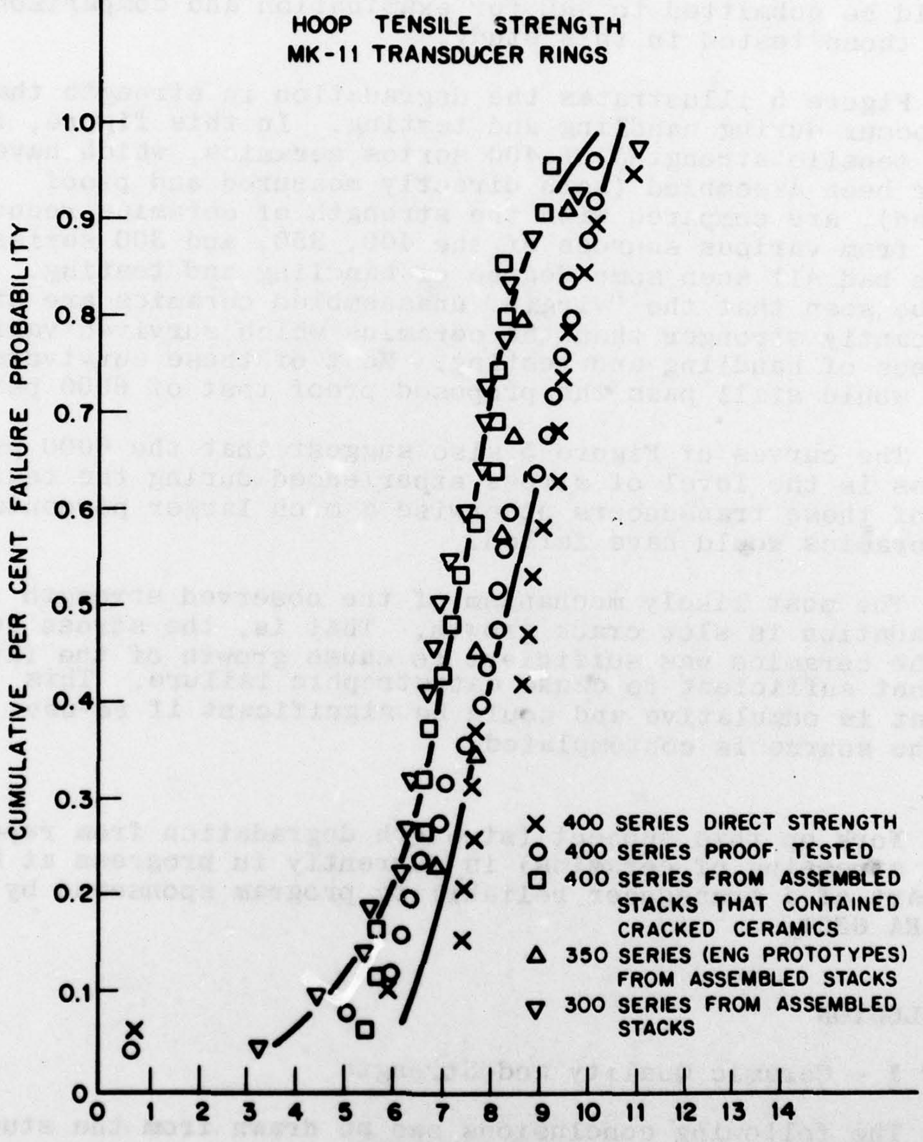

Fig. 5 — Measured strength distributions

sults suggest a proof test would not be necessary for the General Electric ceramics and sources from GE should survive environmental tests without cracking. Should the GE sources crack in future testing of sources, the ceramics should be submitted to NRL for examination and comparison with those tested in this study.

Figure 5 illustrates the degradation in strength that can occur during handling and testing. In this figure, the hoop tensile strengths of 400 series ceramics, which have never been assembled (both directly measured and proof tested), are compared with the strength of ceramics recovered from various sources of the 400, 350, and 300 series which had all seen some degree of handling and testing. It can be seen that the "virgin" unassembled ceramics are significantly stronger than the ceramics which survived various degrees of handling and testing. Most of these survivors, 80%, would still pass the proposed proof test of 6000 psi.

The curves of Figure 5 also suggest that the 6000 psi stress is the level of stress experienced during the testing of these transducers otherwise a much larger percentage of ceramics would have failed.

The most likely mechanism of the observed strength degradation is slow crack growth. That is, the stress seen by the ceramics was sufficient to cause growth of the flaws but not sufficient to cause catastrophic failure. This effect is cumulative and could be significant if re-use of the source is contemplated.

Work on this subject (strength degradation from repetitive stressing of ceramics) is currently in progress at NRL as part of a transducer reliability program sponsored by NAVSEA 660T.

CONCLUSION

PART I - Ceramic Quality and Strength

The following conclusions can be drawn from the studies of the ceramic:

a) approximately 90% of the Edo-Western ceramics are of good quality and would pass a 6000 psi proof test.
b) the level of 6000 psi is most likely the highest hoop tension seen by the ceramic in handling and testing.
c) 10% of the ceramics which have failed in-service or failed the hoop test show an unusual microstructure

which consists of patches of sub-micron powder. (Figs. 2a, 2b, and 2c).

d) General Electric ceramics are significantly stronger than Edo-Western's and based on all samples studied to date, all would have passed the 6000 psi proof test (Fig. 4).

e) degradation of the strength of the ceramics in the source occurs as a result of environmental testing, shipping and handling and could be important if sources are used more than once (Fig. 5).

TASK 2. ORIGIN OF THE HOOP TENSILE STRESSES IN THE TRANSDUCER STACK UNDER AXIAL COMPRESSION

INTRODUCTION

Earlier experience with the behavior of rubber in hoop tensile apparatus suggested that the hoop stresses in the stack under axial compression were due to the lateral movement of the neoprene spacers under axial compression. The most severe compressive forces are seen by the source under water entry shock.

An investigation of the effect of axial loads in causing fracture of the ceramic rings was carried out. This consisted of experimental studies at NRL and theoretical analysis by P. Huang of NSWC. The experimental study consisted of measurements of the compressive stress necessary to cause fracture of the ceramic. These were carried out on one complete stack and a large number of ministacks consisting of one to four ceramic elements.

ORIGIN OF THE HOOP STRESS IN THE SOURCE STACK

The proposed mechanisms for the production of the hoop stresses can be seen by reference to Fig. 6 which shows a cross section of part of the stack (Rings #2, 3, 4), and Fig. 7 which shows the motion of the neoprene spacer under various axial compressive loads. As the compressive load is increased the neoprene flows into the gap between the spacers and along the flat surface of the ceramic, Fig. 7. The hoop tension in the ceramic is generated by two mechanisms. First, as the neoprene is constrained between the central shaft and the ceramic, it exerts a direct outward force on the ceramic which creates a hoop tension. This force exists even when the shoulder is reduced to zero but rises significantly when the gap is filled and a hydraulic pressure is exerted directly. The second source is due to the friction forces between the neoprene and the ceramic which also induces hoop tension in the ceramic as the neoprene flows across the flat faces of the ceramic (Fig. 7) and is particularly severe at the inner edges of the ceramic.

EXPERIMENTAL STUDIES OF AXIAL COMPRESSION OF THE STACK

The compressive loads were applied through a collar so that the force acted only on the ceramic-neoprene-aluminum elements. The load was continuously increased until fracture

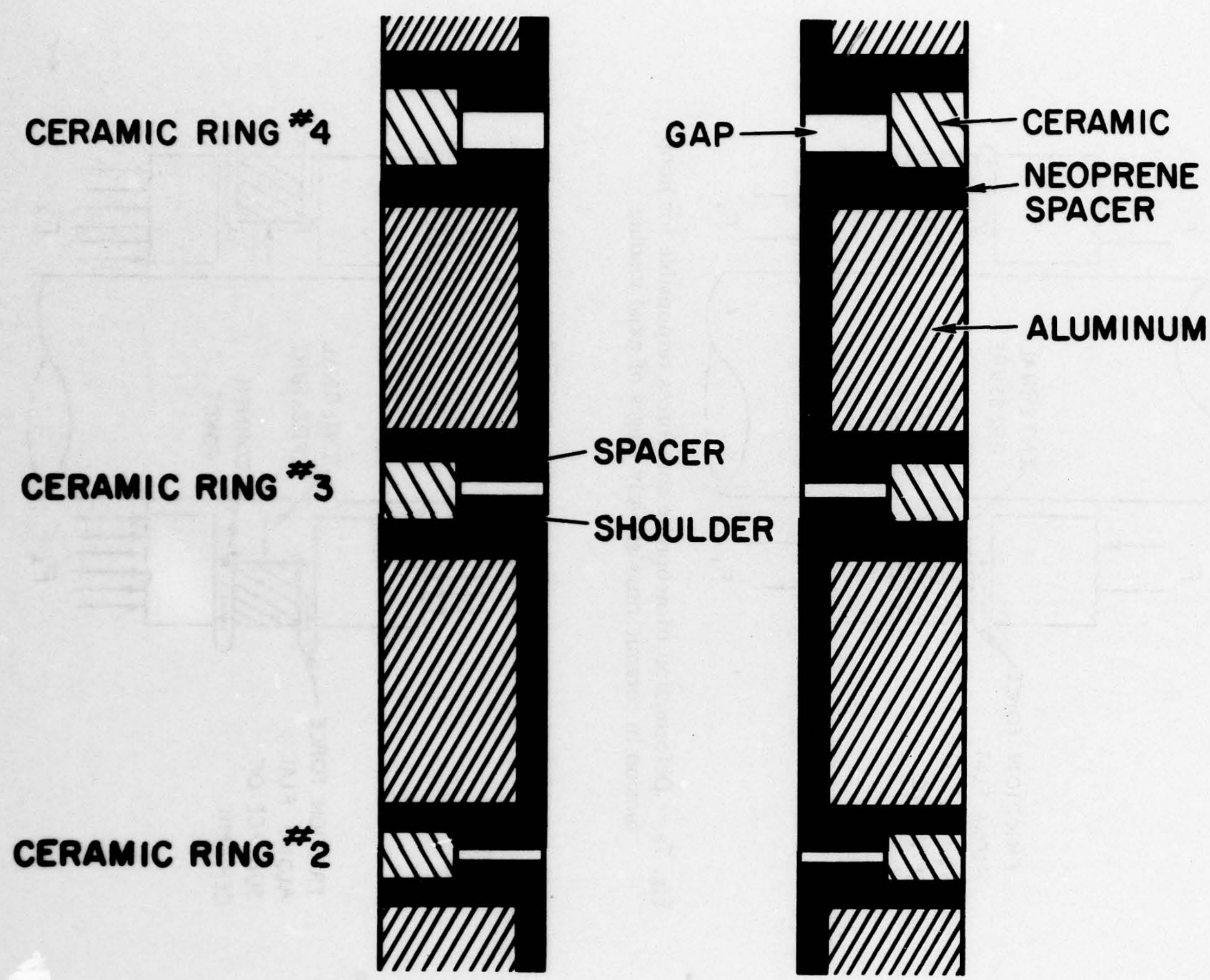

Fig. 6 — Cross-section of part of transducer stack

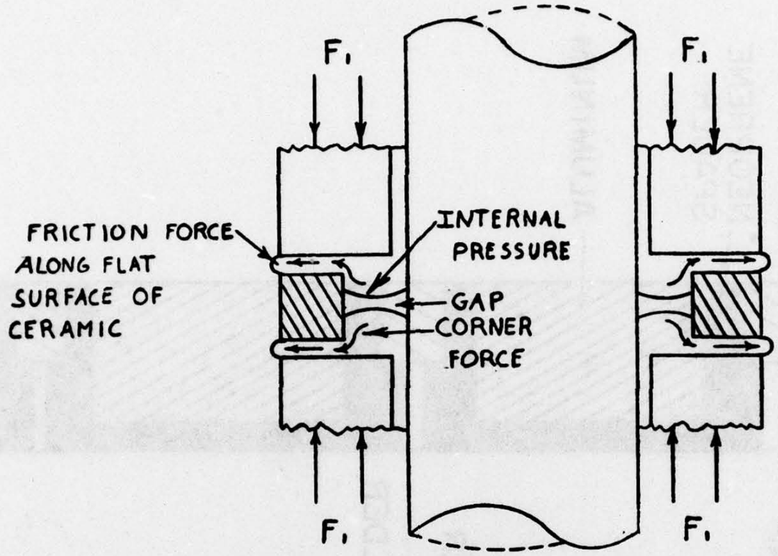

Fig. 7a — Deformation of neoprene and forces responsible for hoop tension in ceramic rings at early stages of axial loading

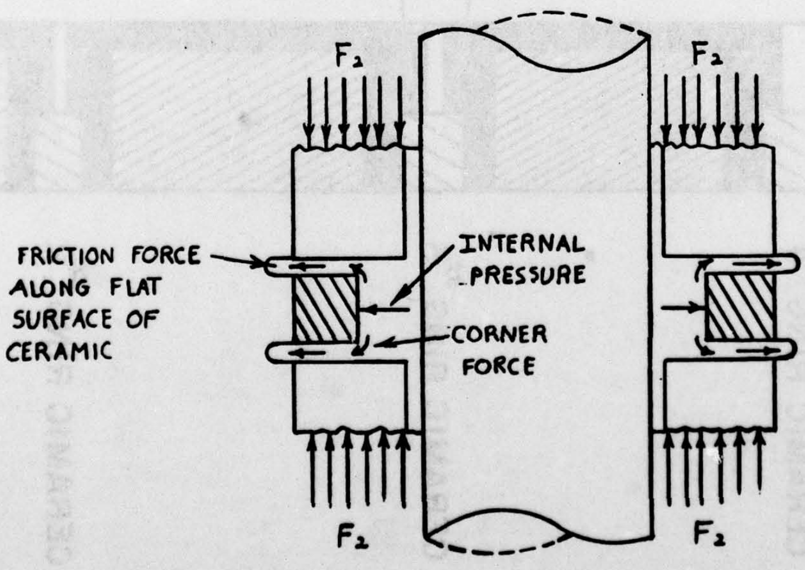

Fig. 7b — Deformation of neoprene and forces responsible for hoop tension in ceramic rings at later stages of axial loading

of one or more of the ceramic elements occurred. The experimental set-up is shown in Fig. 8 for a full stack. In some of the tests hoop strain was monitored during application of the load. This apparatus was also used to study the effects of various modifications of the neoprene spacer and of surface finish of the ceramic on the generation of hoop stress in the ceramic.

Ring #2 (height 0.084") is the shortest and was found to be the most vulnerable to failure by axial loads. The initial efforts were therefore directed toward a study of this ring. The results are given in Table II. Similar tests on rings of other lengths are given in Table III.

Because only a limited number of the shorter rings were available, some of the larger rings were cut down to provide additional specimens. These cut rings are designated by the letter E in Tables II and III.

The conclusion from the data of Table II can be summarized as follows: for the shortest Ring (#2) (.084") reduction of the shoulder of the neoprene to zero provided little or no increase in the axial load needed to cause failure. Further, modification of the spacer by removing the neoprene near the central shaft (see Fig. 9) increased the axial load sustained before fracture by a factor of 1.5. Fine grinding of the flat ceramic surface to reduce the friction force of the neoprene and reduce the flaw size on the edges increased the axial load for failure to about 5 times the original value. Additional polishing of the surface showed little benefit.

Because of the limited number of ceramic rings available, the extensive tests carried out for Ring #2 could not be repeated for all the remaining sizes. A number of tests, however, were carried out and these data are given in Table III. The results of these tests can be summarized as follows:

1. Rings #1 and #3 in the as-received condition are almost as susceptible to failure under axial loads as Ring #2.
2. Use of the undercut spacer for Rings 1 and 3 raises the load sustained before failure by 1000 to 7000 psi over the value for the normal spacer. This in general is substantially more than the increase observed for Ring #2.
3. Completely removing the shoulder which is indicated by the symbol 0/0 in the table also substantially raises the failure load for Rings #1 and #3. This is not true for Ring #2.
4. For Rings 4, 5, 14, 15, 16 failure under axial load

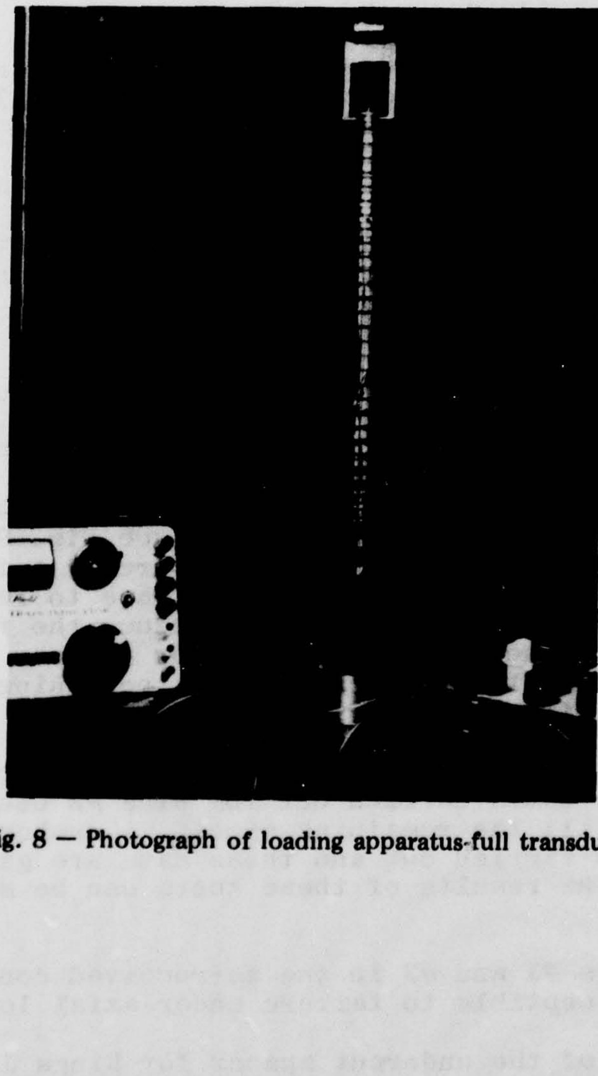

Fig. 8 — Photograph of loading apparatus-full transducer

TABLE II
AXIAL LOAD DATA (Shortest Rings)

Ring	Length	Shoulder[d]	Axial Stress	Ceramic Surface
2B	0.084	0.020/0.040	2,500	As-received
2A	0.084	0.020/0.040	3,180	As-received
2A	0.084	0.020/0.040	3,060	As-received
2B	0.085	0.020/0.040	3,140	As-received
2	0.084	0.030/0.045	2,450[a]	As-received
2	0.084	0.030/0.045	1,250[b]	As-received
2B	0.083	0.022/0.024	2,840	As-received
2B	0.0845	0.018/0.023	1,720	As-received
2A	0.0845	0/0	5,200	As-received
E	0.084	0/0	3,440	Sawed NRL
E	0.084	0/0	3,240	Sawed NRL
E	0.068	0/0	26,200	Fine Grind/Polish
E	0.075	0/0	7,920	Fine Grind/Polish
E	0.0925	0/0	14,800	Fine Grind/Polish
2B	0.084	Undercut Spacer	5,040	As-received
E	0.084	Undercut Spacer	5,040	Sawed NRL
E	0.084	Undercut Spacer	5,360	Sawed NRL
E	0.084	Undercut Spacer	5,600	Sawed NRL
E	0.084	Undercut Spacer	2,400[c]	Sawed NRL
E	0.084	Undercut Space	14,880	Fine Grind NRL
E	0.084	Undercut Spacer	18,880	Fine Grind NRL
E	0.084	Undercut Spacer	15,100	Fine Grind NRL
E	0.084	Undercut Spacer	9,100	Fine Grind NRL

[a] 4 ring mini stack

[b] Full stack

[c] Machining chip

[d] The numbers refer to the height of the upper and lower shoulder. Thus 20/40 designate the normal shoulder and 0/0 indicates the shoulder has been removed completely.

In an earlier draft of this report, and in oral presentations, two additional values of less than 1000 psi were reported on specimens which showed a glassy microstructure. Mr. Bonnema of Edo-Western suggested that these glassy structures might be due to an organic contaminant introduced before testing. This suggestion was confirmed at NRL. Both of these rings had been machined at NRL and it is probable that the organic contaminant was introduced into the crack formed during machining. These results are therefore not relevant to the commercial production of ceramics and were deleted from the table.

TABLE III
AXIAL LOAD DATA (All other rings tested)

Ring	Length	Shoulder	Axial Stress	Ceramic Surface
1A	0.115	0.020/0.04	3,600	As-received
3	0.115	(Standard)	1,600[a]	As-received
3B	0.115	0.020/0.04	1,200	As-received
3/4B	0.113	0.0455/0.030	4,000[b]	As-received
1A	0.115	Undercut Spacer	6,840	As-received
3A	0.113	Undercut Spacer	9,400	As-received
1A	0.116	Undercut Spacer	6,100	As-received
1B	0.116	Undercut Spacer	12,200	As-received
3A	0.112	Undercut Spacer	9,000	As-received
1A	0.116	Undercut Spacer	8,400	As-received
3A	0.1135	0/0	24,400	As-received
1A	0.116	0/0	12,200	As-received
E	0.1035	0/0	35,000	Ground/Polished
E	0.1325	0/0	25,600	Ground/Polished
4B	0.143	0.027/0.032	10,400	As-received
4B	0.1475	0.032/0.028	7,280[c]	As-received
4A	0.144	0/0	20,800	As-received
E	0.1435	0/0	26,400	Ground/Polished
5B	0.1775	0.03/0.04	12,300	As-received
5B	0.178	0.034/0.048	13,200	As-received
5A	0.180	0.040/0.032	14,000	As-received
E	0.17	0/0	20,700	Ground/Polished
E	0.177	0/0	26,800	Ground/Polished
E	0.2075	0/0	27,000	Ground/Polished
E	0.2760	0/0	12,800	Ground/Polished
E	0.3300	0/0	40,800	Ground/Polished
E	(?)	0/0	28,800	Ground/Polished
14B	0.5215	0.040/0.030	12,000[d]	As-received
15A	0.551	0.040/0.030	14,400	As-received
15A	0.550	0.040/0.030	18,500	As-received
16A	0.550	0.040/0.030	22,200	As-received
16A	0.550	0.035/0.040	14,300	As-received
16B	0.553	0.040/0.040	11,400	As-received

E Experimental Rings (prepared from Edo-W Rings)

a Glued ring

b 2 ring stack

c 2nd cycle

d 3 ring stack

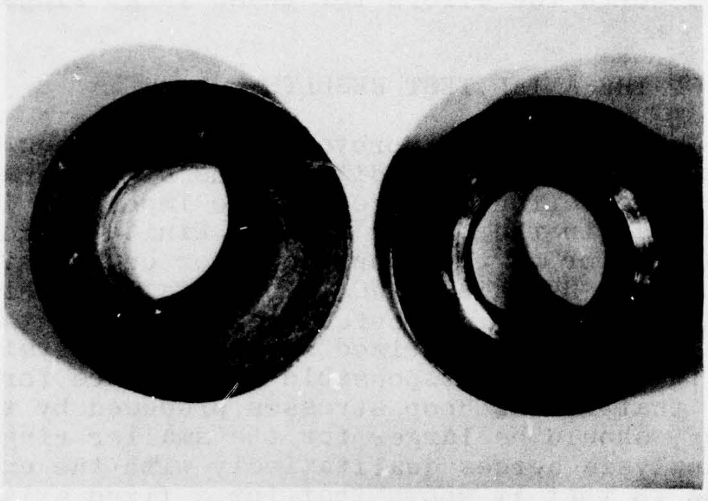

Fig. 9a — Normal spacer at left undercut spacer at right

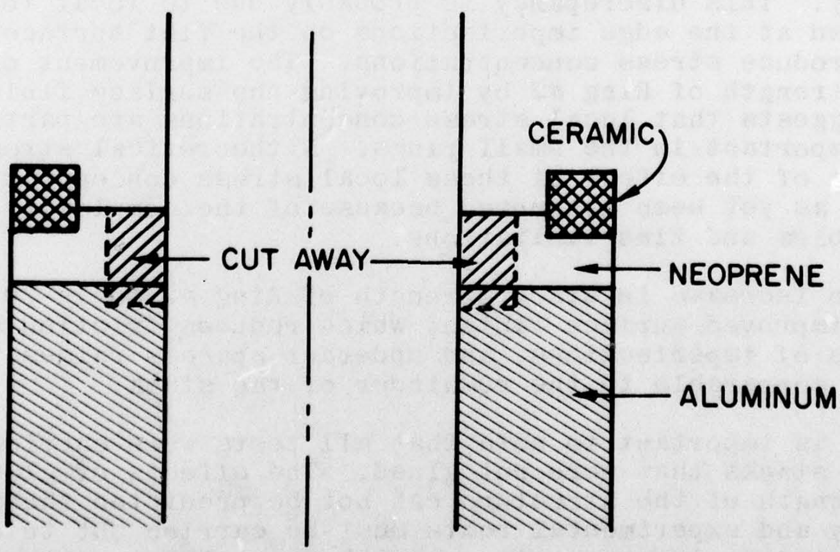

Fig. 9b — Cross-section of undercut spacer

occurs at nominal values of 10-20,000 psi for the normal shoulder (20/40) and the ceramic in the as-received condition.

5. Improving the surface finish of these longer rings raises the axial load to 12-40,000 psi at failure. Since a large scatter exists in these values, it appears that any improvement due to spacer modification or ceramic finish would not be worth the effort for these large rings.

DISCUSSION OF THE AXIAL TEST RESULTS

The relatively small improvement in the stack strength of Rings #2 by the various modifications of the space suggests that the frictional force is more important in the small rings than in the longer rings. Finite element analysis of the behavior of the neoprene under compression was carried out by P. Huang of NSWC. The details of his study are given in the design review report and his results will be briefly summarized here. The analysis predicts that the stresses responsible for failure for a fixed axial load, that is the hoop stresses produced by the neoprene spacer, should be larger for the smaller rings (e.g. #2). His analysis agrees qualitatively with the experimental observations in that it shows that for a fixed axial load the stress should be higher in the shorter rings. The theory, however, predicts lower values than actually observed experimentally. This discrepancy is probably due to local forces developed at the edge imperfections on the flat surface which produce stress concentrations. The improvement of the stack strength of Ring #2 by improving the surface finish also suggests that local stress concentrations are particularly important in the small rings. A theoretical stress analysis of the effect of these local stress concentrations has not as yet been attempted because of the complexity of the problem and time limitations.

The increase in stack strength of Ring #2 to 10-20,000 psi by improved surface finish, which reduces friction and the size of imperfections, and undercut spacers raises it to a value comparable to the remainder of the stack.

It is important to note that all tests were carried out on mini-stacks that were not glued. The effects of glue on the strength of the structure can not be predicted theoretically and experimental tests must be carried out to determine if the improvements noted above will be retained when the joints are bonded. These strength tests are essential and will be carried out as soon as specimens (glued ministacks) are received from Bendix.

SUMMARY

Task 1

In summary, this investigation has shown that 10% of the Edo-Western ceramics used in the Bendix source are weak, that is, they fail at hoop tensile stresses of 5000 psi or less, and a few fail at stresses as low as 1000 psi. It was found that a proof test of the elements of 6000 psi would eliminate the weak ceramics without damaging the survivors.

All in-service failures (from environmental testing or handling) were found to occur in ceramic elements which contained large flaws or other defects. The strength of these was calculated to be 6000 psi or less, and the strength distribution was significantly different from normal Edo-Western ceramics. The fracture of the in-service failed elements was due to hoop tension which arises from the action of the neoprene spacer under axial compression. All service failures occurred either at solder joints or from edge defects at the non-bonded side of the element.

Strength degradation was found in Edo-Western ceramics that had seen either shipping and handling or environmental testing. This degradation could be significant if re-use of the source is planned.

Strength tests of General Electric ceramics (including a 6000 psi proof test) showed that all the General Electric elements were stronger than 6000 psi and on the average 1500 psi stronger than Edo-Western.

Task 2

It was shown that the hoop stresses which cause failure of the ceramic arise from the motion of the neoprene spacer under axial compression. Tests made by axial loading of a full stack and a number of mini-stacks containing one to four rings showed that the shortest Ring (#2) is the most vulnerable to fracture under axial loading. Experimental work at NRL supplemented by theoretical analysis at NSWC showed that two mechanisms were responsible for the development of hoop stress in the ceramic under axial load. The first is the lateral expansion of the neoprene, thereby filling the gap between the spacers and then exerting outward pressure on the ceramic resulting in hoop tension. The source of hoop tension is the friction between the ceramic and the neoprene. Under axial compression, the neoprene flows over the surface of the ceramic and friction sets up a hoop tension in the ceramic. Modification of the spacer to provide more space for the neoprene to flow resulted in

an increase of 1.5 times in the axial force necessary to cause fracture of the ceramic in the most vulnerable regions (the three smallest rings). Further modification of the spacer combined with an improved surface finish of the ceramic increased the axial failure load for Ring #2 by 5 times. These changes raise the most vulnerable region to values equal to those of the larger rings.

All stack tests were made on unbonded ceramics. The effects of bonding on the resistance of the stack to fracture under axial compression are not known and may be significant. Tests will be made as soon as bonded mini-stacks are made available by Bendix.

ACKNOWLEDGMENT

The authors would like to acknowledge the following people for assistance: J. Stasiewicz, Tracor, for carrying out preliminary measurements of axial strengths; S. Morey, NRL, for scanning electron micrographs of fracture surfaces; and D. Mulville, NRL, for discussion of stress analysis.

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